Radiation Sensor with Electro-thermal Gain

FIELD OF THE INVENTION

This invention relates to microsensors that are constructed utilizing semiconductor fabrication processes and, more particularly, to a thermal radiation sensor. The sensor us useful for detecting low level radiation absorbed in microstructures at power levels of a nanoWatt and less into microstructures. This invention is typically used for the detection of low level infrared radiation. However, the low level radiation may be comprised of any electromagnetic radiation absorbed into a pyro-optical film within the radiation sensor and thus may include wavelengths ranging from the ultraviolet, visible, near infrared, far infrared, and into the millimeter wave regions. The present invention can be devised as a single sensor element or as an array of pixels including a focal plane array.

BACKGROUND OF THE INVENTION

There are many types of infrared or low level radiation sensors for imaging and non-imaging applications. The most widely used infrared imagers employ photon detection and thermal detection. Most thermal detectors utilize sensor elements including thermistors, piezoelectric, and ferroelectric elements that change electrical characteristics with temperature. In each of these sensor types there is a direct electrical connection between the sensor element and the readout electronics or readout integrated circuit ROIC. A limitation in this type of radiation sensor is that the direct electrical connection mentioned serves as a pick-up for parasitic noise sources due to capacitive, inductive, and electromagnetic pick-up of unwanted signal levels. The present invention has no

electrical connection between the sensor structures for low level radiation and the readout ROIC and thus avoids many of the aforementioned parasitic noise problems.

Micromachining has been developed as a means for accurately fabricating small structures and is now being applied to microstructures for radiation sensors. Such processing involves the selective etching of a substrate and the deposition thereon of layers of thin films . Various sacrificial layers are employed to enable the fabrication of relatively complex interactive structures. This technology is generally referred to as MOEMS (micro-optical electromechanical systems) technology and is utilized in a wide range of application devices. In the present invention we utilize MOEMS technology to fabricate microplatforms that contain a pyro-optical film as a key component of a radiation sensor system. These microplatforms are a key component within the radiation sensor system which includes a high level source of photonic radiation and a detector for the modulated high level photonic beam. The pyro-optical film modulates the amplitude of the photonic carrier beam to the detector. Thus, the photonic carrier beam may also be referred to as the interrogation beam. The high level photonic radiation is typically a visible or near infrared wavelength beam. The photon detector is typically a two-dimensional array of silicon charge coupled diodes (CCD) or CMOS silicon diodes. When low level radiation is incident on a pyro-optical thin film, an incremental heating occurs which in turn causes a change in the transmissivity or reflectivity of the interrogation carrier beam. This change in the pyro-optical characteristics modulates the amplitude of a photonic beam exiting to an ROIC detector. In the present invention the resulting video signal output from the ROIC and associated circuitry is highly sensitive to the amplitude of incident low level radiation.

A thermal imager that includes an infrared sensitive light valve and a light source arranged to illuminate the valve was described by Elliott and Watton in U.S. Patent No. 4,594,507. This imager contains an infrared sensitive optically active liquid crystal cell and an analyzer adjusted to near extinction. An optical processor comprising a lens and an apodized stop filter lies in the light path between the valve and the detector array. The thermal imager described in this patent uses an interrogation light beam but does not mention microplatforms, microstructures, or thermal gain.

An infrared sensor scheme is described and without thermal gain by Hanson in U.S. Patent No. 5,512,748 in which an infrared sensitive film is used to amplitude modulate a photonic carrier beam. This patent describes a focal plane array including a plurality of thermal sensors mounted on a substrate. An image is formed on an infrared sensitive film layer in response to infrared radiation from a scene. Electromagnetic radiation from a source is used to reproduce or transfer the image from the thermal sensors onto the first surface of the substrate. In the Hanson patent there is no mention made of a pyro-optical film in which the absorption of a visible or near infrared carrier beam increases with temperature to achieve a photo-thermal gain.

Cross et al in U.S. Patent No. 4.994,672 describe an infrared imaging system which includes a pyro-optic sensor for receiving a low level thermal image on one of its sides, the sensor exhibiting a substantial change in refractive index in response to changes in its temperature. A high level light beam is projected onto the sensor and locally reflected in accordance with local changes in the refractive index of a pyro-optic film. This detector and imager description does not mention any structures or techniques for obtaining thermal gain.

Grossman and Reintsema in US Patent No. 6,323,486 B1 describe a bolometer in which the vanadium oxide sensor film is heated from a current source to achieve a negative electrothermal feedback with electrical readout. This teaching does not mention using vanadium oxide or other film to modulate a photonic light beam and the use of a CCD readout. The use of a positive feedback factor to enhance the responsivity is not mentioned.

Blodgett et al in US Patent 5,608,568 describre using a thin film of vanadium oxide as a spatial light ;modulator in which the thermally isolated thin film of vanadium oxide is electrically heated to proviide a bistable reflection of incident, optical radiation. Micromachined, thermally isolated platforms are not mentioned. This teaching does not describe a feature sensitive to low level incident radiation.

It is an object of this invention to provide an improved radiation sensor wherein micromachining of a thermally isolated platform is used with selected pyro-optical thin films to accomplish a sensor with thermal gain. This means of thermal gain is powered by the high level carrier beam.

It is another object of this invention to provide a pyro-optical sensor with an increased sensitivity to low level radiation wherein the readout noise and photonic noise contributions to the system output are relatively reduced. The result is a decrease in the net equivalent temperature differential NETD of a source of low level radiation that can be detected by the radiation sensor.

SUMMARY OF THE INVENTION

In the present invention we describe a radiation sensor for low level radiation where typically less than a nanoWatt is absorbed in a pyro-optical microstructure. The radiation sensor contains an absorbing microplatform that is thermally isolated from a substrate, a high level interrogating carrier beam and source, and a sensitive detector for the carrier beam exiting the microplatform. The carrier beam is modulated by the pyro-optical thin film in the microplatform and detected by the ROIC. The microplatform contains an integral pyro-optical film which modulates the high level photonic carrier source in addition to and an electrical heater element. The low level radiation to be sensed is partially absorbed on the microplatform causing a first incremental increase in temperature. The intensity of the photonic carrier beam exiting the microplatform is amplitude modulated by the temperature of the pyro-optical film.

The microplatform contains the integral pyro-optical film and the heater element where (1) a first source of low level radiation or heat is incident upon the sensor platform and partially absorbed causing a first incremental heating of said film, (2) a power source of constant voltage or constant current driving the resistive heater element with a thermal coefficient of resistance thereby causing a further incremental heating of the microplatform, and where the combined temperature rise of the pyro-optical film due to both the first and second incremental temperature increases is greater than that due to the first source of radiation alone, and (3) used with an optical carrier beam for readout by a photonic CCD or CMOS readout ROIC. The structure with cooperating sensing and heating structures comprise a sensitive sensor for low level

radiation. with an internal photonic carrier beam for interrogating the temperature of the pyro-optical film.

The resistor heater establishes a quiescent temperature level T_Q or T_{oo} for the microplatform which is several degrees above the heat sink temperature of the underlying substrate. Typically the first incremental heating is on the order of microdegrees to millidegrees Centigrade. The first incremental heating level ΔT_{ir} causes a further increase in the electrical power dissipated from the heater element in the microplatform due to it's thermal coefficient of resistivity. The amplitude of the second incremental heating is ultimately limited by the nonlinearity of the thermal hysteresis of the pyro-optical film. The enhanced heating of the microplatform in excess of that obtained from the low level radiation alone is a stable gain maintained around the quiescent temperature operating point T_Q.

The electro-thermal gain of the present invention can be described further by examining the basic theory of optical absorption in the microplatform. Figure 1 shows the two incident radiation beams and the and the exiting high level or carrier beam with the pyro-optical film 100. Symbols used are defined for amplitude of the incident low level radiation Φ_{ir}, amplitude of incident carrier beam Φ_{ci} ,and amplitude of exiting carrier beam Φ_{co}. The amplitude Φ_{co} is modulated by the temperature of the microplatform; in this example the transmission amplitude is modulated.

Typical hysteresis 200 of a pyro-optical thin film such as vanadium oxide as a function of temperature is shown in Fig. 2. The vertical axis is the reflectance or transmission transfer function for the high level beam Φ_{co} . The exiting carrier amplitude Φ_{co} corresponding to the quiescent temperature is defined as Φ_{oo}. A pyro-

optical film heated from a low temperature value reaches a quiescent temperature of Φ_{oo} in a situation without incident beams Φ_{ci} and Φ_{ir} due to the heater power V^2 / R_o where the voltage V is impressed across the heater of quiescent resistance R_o . The low level incident beam Φ_{ir} is absorbed in the pyro-optical film 100. For the situation without any change in R_o the temperature of the film increases by the increment ΔT_{ir} . The total increase T in temperature above heat sink temperature due to both the low level incident heating and the electrical heater element is:

$$\Delta T = \Delta T_{\iota\rho} + \Delta T_{elec}$$

The temperature increase is due to the electrical power V^2 / R and inversely proportional to the thermal conductivity G of the microplatform tether beams.

$$\Delta T_{elec} = V_o^{\,2} / G R$$

The resistance R of the heater element is the quiescent resistance R_Q reduced by the first incremental heating.

$$R = R_Q - \Delta R_{\iota\rho}$$

The heater element change of resistance $\Delta R_{\iota\rho}$ due to the first increment of heating is:

$$\Delta R_{\iota\rho} = k_{\iota\rho} \quad \Delta T_{\iota\rho}$$

The quiescent temperature T_Q of the heater is determined by the quiescent resistance R_Q

$$T_Q = V_o^{\,2} / G R_Q$$

From the above relationships, the final microplatform temperature T

$$T - T_Q = \Delta T = (1 + k_{ir} \; V_o^{\,2} / R) \quad \Delta T_{ir}$$

where $\Delta T >> \Delta T_{ir}$.

The ratio of the final increase in temperature ΔT to the first incremental heating ΔT_{ir} is the electro-thermal gain factor G_{et}:

$$G_{et} = 1 + k_{ir} V_o / R$$

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 First and second sources incident on a film of pyro-optical material

Fig. 2 Example of a typical pyro-optical hysteresis with parameters defined

Fig. 3 is a schematic view of a radiation sensor system providing thermal gain with transmission of the second source of radiation through the MEMS plane

Fig. 4 is a schematic view of a radiation sensor system providing thermal gain with reflection of the second source of radiation from the MEMS plane

Fig. 5 is a schematic side view of a transmission-type microplatform pixel containing a pyro-optical film with electro-thermal gain

Fig. 6 is a schematic side view of a reflecting-type microplatform pixel containing a pyro-optical film with electro-thermal gain

Fig. 7 is a schematic top view of a 2 x 2 array of microplatforms, in which the vanadium oxide serves as both the pyro-optical modulating film and also as the resistive heater element with a negative temperature coefficient of resistance TCR

DETAILED DESCRIPTION OF THE INVENTION

We describe a radiation sensor which contains an internal photonic carrier beam to monitor extremely small variations in the temperature of a microplatform. The reflection or transmission of the exiting photonic carrier beam with respect to a microplatform is monitored by a detector. The present invention uses micro-opto-electromechanical-systems MOEMS technology to form a single microplatform or an array of microplatforms for detecting low level radiation. Each microplatform contains a resistive heater with a high temperature coefficient of resistance. Each resistive heater is driven by a current or voltage source as appropriate to cause the microplatform to heat with the absorption of low level incident radiation.

Fig. 1 is a block diagram of a radiation sensor constructed in accordance with the present invention. During operation for the application of thermal radiation detection, emission from scene 301 is received by collection optics 302 and focused on the microplatform 300. In many cases a chopper is placed in the beam of low level radiation 305 between the optics 302 and the microplatform 300 thereby enabling a synchronized detection function. Source 301 may be any source of low level radiation that can be focused onto and absorbed into the microplatform. The low level radiation beam 305 is absorbed in the microplatform 300 causing an incremental increase in the temperature of the microplatform 300. In a typical application the source 301 is a scene of objects that emit thermal radiation and the microplatform structure 300 consists of an array which provide means of imaging through the sensor system of Fig. 3. In the case of imaging, the two-dimensional source 301 is transferred as a scene to the microplatform with an

incremental temperature heated pattern on the microplatform array corresponding to the scene 301. As with all thermal imaging systems, the invention is especially useful when imaging by means of visual wavelengths is unavailable, such as in the dark or when vision is impaired by smoke, dust, or other particles. The optics 302 are well known in the art of thermal imaging and may be any one of a number of systems of lenses. Optics 302 focus the source 301 on the microplatform 300 in order to sense the radiance of the incident infrared radiation 305 it receives. Collection optics 302 may include one or more lenses made of material that transmits infrared radiation such as germanium. The placement of optics 302 and optional chopper with respect to the microplatform 300 is accomplished using well known principles of optical design as applied to thermal imaging systems. The low level radiation may alternatively be focused onto the microplatform 300 using Cassegrainian reflective optics. Nonthermal sources of low level radiation such as photonic bursts of energy of visible or ultraviolet radiation can be focused onto the microplatform 300 also by transmissive or reflective collection optics. Low level radiation from millimeter/microwave sources can be directed or focused onto the microplatform by structures including directional antennas and reflectors effective at these very long wavelengths compared to infrared.

An array of microplatforms 300 may be used as part of a wide variety of low level radiation detectors and thermal imaging systems. The invention may be used with either "staring" or "scanning" detection means. A staring detector is a large area detector onto which the entire thermal image is focused at once and read out electronically. A scanning detector uses a mirror or tethered means to sweep the low level radiation across the microplatform array.. Usually, although not necessary for the invention, both types of

detection means consist of a plurality of sensor elements, with the output of each thermal sensor representing a portion of the viewed scene. For example, the output of each microplatform 300 may represent a single pixel of the total image. Thermal sensors described in Fig. 3 incorporating the present invention may be particularly beneficial for use in high density arrays 300 and with high density visual displays.

High level light source 303 is provided for use in transferring the low level radiation spot or pattern formed on the microplatform or microplatforms 300 to photosensors 304 disposed in the path of the high level radiation beam 306 from source 303 as illustrated in Fig. 3. Photosensor 304 detects the beam 306 after it is modulated by the transmission through the microplatform. The photosensor 304 can be an array for the case of imaging in conjunction with an array of microplatforms 300. For many applications, optical source 303 preferably provides electromagnetic radiation in the visible or near infrared spectrum to match the sensitivity spectrum of silicon used in the photodetector 304. The use of the high level beam 306 from source 303 to transfer spots or images from low level sources to photosensor 304 results in a conversion of the thermal temperature increment in microplatform 300 into modulation of the high level carrier beam detected by the photodetector 304.

Electronics are used to format the electrical signal output in photodetector 304. Electronics are provided to perform selected operations on the photodetector output including digitization, synchronizing with the chopper, zooming, general image processing, formatting for a display with techniques well known to the art of imaging and low level signal processing. The large signal level of the detected high level beam 306 contains a small signal modulation due to the low level beam 305. Image processing

within or in cascade with the photodetector 304 is used to eliminate the large signal component from 306 to provide an unbiased output representative of the intensity pattern of the low level incident beam 305. For the display application embodiment, a special viewing device such as a CRT or LCD display is driven by the electronics. The image on a display obtained through the electronics from the radiation sensor system is typically a visual representation of the radiance image of the microplatform 300 corresponding to points on the two dimensional scene 301. The radiation sensor system may include digitization electronics so that the signals can be stored and processed as digital data. This requires sampling, storage, image subtraction and processing circuits which are well known in the field of video and graphics processing and be included as part of the electronics. The radiation sensor system may function as a radiometer to provide temperature measurements of radiant energy sources present in source 301 or other sources focused onto the microplatform 300.

A chopper wheel or other optical switching device is generally used to synchronously interrupt the beam of low level radiation 305 to the microplatform 300 thereby providing a reference signal and a bias signal. Collection optics 302 and the chopper cooperate to form a reference temperature increment on the microplatform 300 corresponding to the background radiance. The electromagnetic energy 306 from light source 303 in cooperation with photosensor 304 will produce a signal corresponding to the total radiance filtered by the chopper from source 301 during any frame of time. Electronics included in the photodetector 304 and associated electronic processing will cooperate with each other to process the bias signal and the reference signal to generate an unbiased signal which may be transformed into a data stream for display or storage in a memory

for later processing. The process of establishing a reference signal and receiving a bias signal is repeated in succession for a stream of video images in the case of imaging. The present invention contemplates either establishing a reference signal before or after the detection of a bias signal, or establishing a reference signal before or after a predetermined number of bias signals have been received and processed.

The electronics preferably include a control circuit to operate a thermoelecrtric cooler/heater to adjust the temperature of the substrate 300 to produce optimum sensitivity.

Figure 4 shows an embodiment with a microplatform 400 which modulates the intensity of reflected high level incident radiation 407. This embodiment differs from the case of Fig. 3 which uses a microplatform to modulate the intensity of transmitted high level incident radiation. In the reflection configuration of Fig. 4 a high level visible or near infrared photonic source 403 is formed into a collimated or near collimated high level beam 407 by optics 406. The high level beam reflected from the microplatform 404 may also be focused onto the photodetector 404 with separate optics. The high level beam 407 is reflected from the microplatform or array of microplatforms 400 to terminate in the photodetector or array of photodetectors 404. The source of low level radiation 402 focussed by optics 401 onto the plane of the microplatform 400 thereby causing an incremental heating of the microplatform or array of microplatforms in correspondence to the cross section of the focused low level beam 408. The electronics 405 may be external from the photodetector 404 or may be integrated into the substrate of photodetector 404. The basic functions of the reflecting radiation sensor system of Fig. 4

are similar to that of the transmissive sensor system of Fig. 3 except that in the Fig. 4 case the high level beam 407 is reflected from the MOEMS microplatform plane.

One embodiment of the Fig. 4 configuration places the high level source 403 and the photodetector 404 within the area of the low level beam 408 thereby providing an approximately normally-incident high level and low level illumination of the microplatform. In this embodiment both the high level source 403 and the photodetector 404 partially shadow the incident low level radiation 408 onto the microplatform. This embodiment has the advantage of compactness and design simplicity.

Figure 5 shows an enlarged schematic representation of two microplatforms corresponding to elements in the MOEMS plane 300 of the transmissive embodiment. The incident high level beam 502 passes through the microplatform to terminate in the photodetector disposed in alignment and adjacent to the substrate 509. The microplatform consists of a base plane 506 and tether beam 508 providing a support and thermal isolation framework for the platform. Disposed on the base plane 506 is the pyro-optical film and resistive heater structures 501 which modulate the intensity of the carrier beam 502. The incident low level radiation 503 is partially absorbed in the microplatform causing the desired incremental heating effect for the platform or MOEMS pixel. A surface structure 505 can be added to the base plane 506 to increase absorption of the incident low level radiation beam 503. A patterned conductive film 507 selectively transmits the high level beam through to the photodetector. Patterned film 507 selects that portion of the beam which is modulated by the pyro-optic film and rejects that portion which is not modulated thereby improving the overall signal to noise ratio of the radiation sensor system. Film 507 also forms the electrical power supply for

the heater element within each microplatform. The tetherbeams within 608 include the electrical interconnects to the underlying bus 507. The two microplatforms of Fig. 5 can be fabricated as a one or two dimensional array on substrate 509. Substrate 509 is optically transparent to the carrier beam 502.

The two example microplatforms in embodiment Fig. 5 are fabricated using micromachining technology involving patterned depositions and a sacrificial layer onto the substrate 509. The embodiment of Fig. 5 is fabricated on a quartz or other substrate 509 transparent to the high level carrier beam 502. An opaque metal 507 including aluminum is sputtered with a thickness of 100 nm or more and patterned onto the substrate 509. Next a sacrificial layer including polyimide is spun on and patterned to accommodate the anchors from the tether beams 508 of the microplatform plane 506.. The microplatform plane 508 and tetherbeams are obtained by CVD deposition of silicon dioxide at low temperature with appropriate lithographic patterning. The base plane 506 is covered with a pyro-optical film and also appropriately patterned using lithography. Next vias are patterned into the sacrificial film to accomodate the electrical interconnect. Structure 506 contains the pyro-optical film formed and patterned from material selected from the group including vanadium oxide, aluminum gallium arsenide, indium gallium nitride, indium gallium arsenide, indium antimonide, antimony sulfoiodide, barium titanate, barium strontium titanatate, antimony sulphur iodide, and lead lanthanum zirconate titanate, and crystallites of various semiconductors. In this preferred embodiment the patterned pyro-optical film 506 also serves as the heating element. Next vias are etched with reactive ion etching through the tetherbeam structure in 508 to expose the surface of 507. This via is cut for the purpose of making the electrical

connection to the power bus 507. The interconnect also within 501 from the heater element to the power bus 507 is now sputter deposited and patterned. Level 501 also contains the patterned metallic overlay of preferably a titanium-gold sandwich that forms the interconnect between the power bus 507 and the heating element 501. The pyro-optical material which is specifically selected to form film layer 501 will depend upon the wavelength of the high level radiation that is to be modulated, the response wavelength window of the photodetector, and the desired absorption of the low level beam 503 into film 501. A topmounted film or structure 505 to facilitate the absorption of low level radiation 503 may be deposited and patterned appropriately. The film 505 may be a carbon polymer or a structure with dipole resonance to absorb incident far infrared or millimeter wave radiation . The films 501 and 505 may be passivated with a protective film that is not attacked by the process step of removing the sacrificial film. The sacrificial film underlying the base plane 501 is removed at a processing step near the completion of processing. Polyimide is a compatible sacrificial layer for this embodiment and is removed using an oxygen plasma.

Figure 6 describes the preferred embodiment of a radiation sensor MOEMS plane that modulates the reflected amplitude of high level carrier beam 602 . The reflective microplatform schematic of two platforms in Fig. 6 is fabricated similarly to the embodiment of Fig. 5 except that the power bus contains two levels of conducting film 607, 619 and where film 607 also serves an optical reflector 607 for the high level carrier beam 602. The microplatform may be a single microplatform but is more typically an array of microplatforms that are mated to the reflective configuration of the photodetectors as illustrated in Fig. 4. The film 607 covering the substrate reflects the

high level beam 602 which has a double-pass through the pyro-optical film 601. An additional modulation effect which increases the index of modulation is obtained with the double-pass of beam 602. The reflected beam 602 of Fig. 6 corrresponds to the source beam 407 modulated by the MOEMS plane 400 and exiting to the photodetector 404. The fabrication process for the reflective MOEMS plane of Fig. 6 is similar to that of the transmissive MOEMS plane of Fig. 5. The only basic difference is that the substrate 609 is typically silicon and is not transparent to the high level carrier beam as is the case in the Fig. 5 embodiment. Also the Fig. 6 embodiment contains an additional unpatterned conductive film 619 of sputtered aluminum . The film 607 forms the second power bus. Patterned vias in 608 provide the electrical connection for the sputtered interconnects on the microplatform 606 and into the respective underlying power bus lines. The power bus of Fig. 6 is shown to be driven from voltage sources as necessary for the heaters with a negative temperature coefficient of resistance.

Figure 7 is a schematic top view of a group of 4 arrayed microplatforms 71 showing the electrical interconnect 73 delivering electrical power to the vanadium oxide film heater 75. The tetherbeams 72 supporting each pixel contain the electrical interconnect 73 and are further electrically connected to the underlying power bus through vias 74. The patterned vanadium oxide 75 serves as both the pyro-optical modulating film and the electrical heater element. The pixel structure 71,72 corresponds to the microplatforms506, 606 of Fig.'s 5 and 6. The platforms 508 and 608 each contain the electrical interconnect to the power bus 507, 607 and 519, 619. The underlying power bus is configured to drive each pixel heater with a constant voltage

source for the case of a vanadium oxide heater with negative temperature coefficient of resistance.

In another preferred embodiment the pyro-optical film is separate from the heater element. For instance, the heater element can be formed of a serpentine pattern of PECVD polysilicon or sputtered tantalum silicide. In this case, the pyro-optical film and the heater element are fabricated as separate structures within the microplatform. In this embodiment, each pixel heater is connected in series and the entire array of microplatforms is driven from a constant current source to achieve the desired electro-thermal gain.

It should be understood that the foregoing description is only illustrative of the invention. Various alternatives and modifications can be devised by those skilled in the art without departing from the invention. Accordingly, the present invention is intended to embrace all such alternatives, modifications and variances which fall within the scope of the appended claims.